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Effect of Low Temperature Thermomechanical Treatment on the Phase Composition and Properties of a Two-Phase Titanium Alloy

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Abstract. By means of X-ray diffraction (XRD) analysis and transmission electron microscopy (TEM), the effect of structural and phase composition on the complex of mechanical properties of the VT16 two-phase titanium alloy after low-temperature thermomechanical treatment (LTTMT) is studied. The features of the α' and β-phases decomposition, including βa-phase with an abnormally large lattice parameter during aging with different soakings are described. The high strength of the alloy (TS=1270–1550 MPa) with a certain margin of ductility (EL=0–10 %) is shown to be achieved by means of low temperature thermomechanical treatment, which included solution treatment (ST) at $T_{st}=\beta_{tr}$-10 °C, cold rolling with a relative reduction ratio of 45 % and subsequent aging at 500 °C for 3 to 24 hours.

INTRODUCTION

Thermomechanical treatment (TMT) of titanium alloys is a promising technological solution not only providing high strength, but also enabling one to maintain satisfactory ductility characteristics [1, 2]. Low temperature (LT) TMT is a type of thermomechanical treatment comprising the steps of quenching, cold working and subsequent aging. For the majority of two-phase titanium alloys, LTTMT is complicated because of a considerable content of aluminum (generally 5 mass % or more), which impedes their cold plastic deformation. The exception to the rule is the alloy VT16, which contains about 3 % of aluminum on average. Therefore, it is possible to make semi-finished products from the alloy by means of cold deformation [3]. However, the phase transition of the second order might occur in β-metastable Ti-alloys with K_β of about 1 [4], and this would definitely result in the physical and mechanical properties. We have already studied the structure, phase composition and properties of the VT16 alloy after ST followed by cold deformation and subsequent continuous heating at a temperature range including its aging temperature range [5, 6]. In [6] the ST heating temperature was taken as ($\beta_{transus}$–10) °C. It provided a structure with the maximum fraction of orthorhombic α''-martensite capable of age hardening and allowed us to eliminate active β-grain growth due to the conservation of the number of primary α-phase particles. The α''-martensite obtained after ST underwent strain-induced transformation according to the scheme α'' → (α'+β_a) during cold plastic deformation with a reduction ratio of 45 %. As a result of accommodative processes taking place due to the difference in the specific volumes of the original (α'') and formed (α') martensite crystal lattices, a β_a-solid solution was formed, with an abnormally large lattice parameter (0.33 nm). In [5] it was found that, during continuous heating of a cold-worked alloy, aging proceeds actively in the temperature range of 400...650 °C. It was attributed to the decomposition of the metastable phases (α', β_a). However, LTTMT might result in embrittlement due to high dislocation density after cold working and to precipitation hardening upon aging. Therefore, the object of the present study is the formation of structure and mechanical properties during the entire LTTMT procedure: ST (quenching) – cold working – aging.

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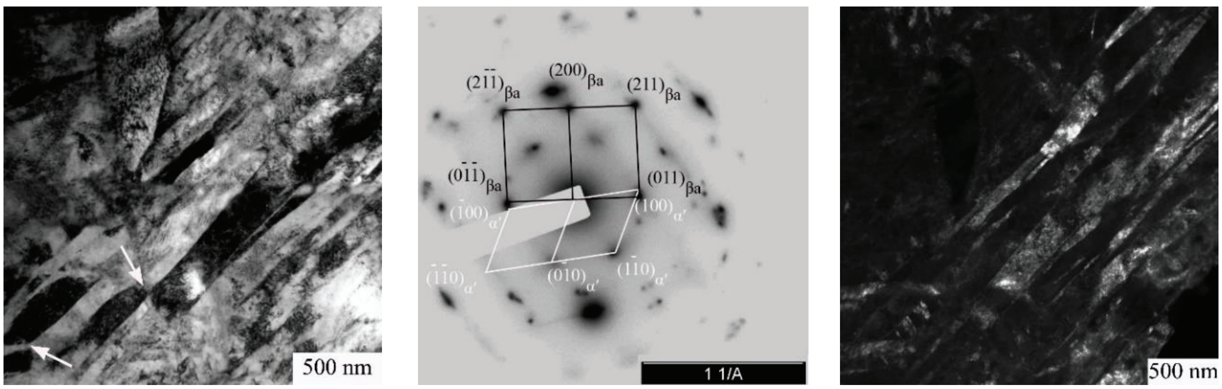
RESULTS AND DISCUSSION

In the present study, 12 mm diameter rods of the VT16 alloy were used, with the following chemical composition: Ti-2.9%Al-4.8Mo-5.1V-0.12O-0.07Fe mass %. Based on the above results, the LTTMT of the specimens was as follows: ST at 850 °C ($T_s = \beta_{transus}$-10 °C) water quenching and cold rolling at a room temperature with a reduction ratio of 45 % was provided by the rolling mill DUO. The rolling route was as follows: circle – oval – 90° rotation of the template – oval [6]. The final operation was aging at 500 °C, with the soaking varying from 3 to 24 hours. The XRD analysis was conducted with the use of a Bruker D8 Advance diffractometer in copper K_α-radiation. TEM investigations were performed on a "JEM-200 CX" microscope. Tensile tests were provided by Instron 3382.

The microstructure of the VT16 alloy after cold rolling was studied on thin foils by TEM. The structure consisted preferably of alternate plates of the α' and β_a-phases (Fig. 1a), as indicated by the interpretation of the electron diffraction pattern (Fig. 1b) and the dark-field images obtained in α'- and β_a-reflections (Fig. 1c, d). It was previously shown in [6] that the above structure had been formed as a result of the strain-induced transformation of α″-martensite. Note that not only the strain-induced transformation, but also the fragmentation and warping of the observed plates took place during cold rolling to 45 % (as indicated by arrows in Fig. 1a).



(a) (b) (c)

FIGURE 1. TEM data on a VT16 rod cold-rolled to 45 %: a – a bright-field image; b – an electron diffraction pattern and its interpretation, zone axes $[001]_{\alpha'}$, $[011]_{\beta a}$; c – a dark-field micrograph in the $(211)_\beta$ reflection

The TEM data is in a good agreement with the XRD analysis. Particularly, the peaks of the HCP α'(α)-phase and the BCC β_a-phase with abnormally great lattice spacing are found in the diffraction patterns of the rod cold-rolled to 45 %.

The peaks of the β_a-phase remained in the diffraction patterns of cold-rolled specimens after 3 hours of aging (Fig. 2).

In addition, the asymmetry of the α(α') peaks is observed, which is typical for the appearance of precipitations of the secondary low temperature α_{LT}-phase with rhombical lattice distortions. Aging with longer soakings lead to the disappearance of abnormal β_a-peaks in the diffraction patterns, as well as to the reduction of α(α') peaks asymmetry, and this indicates the decomposition of α'-martensite starting from 6 hours soaking. The peaks of the β-phase at the typical 2θ are observed ($(200)_\beta$ peak at about 57°). Therefore, we conclude that an increase in soaking time during aging to more than 6 hours has a fixed two-phase (α+β)-state of the alloy in which decomposition products are formed by the diffusion mechanism.

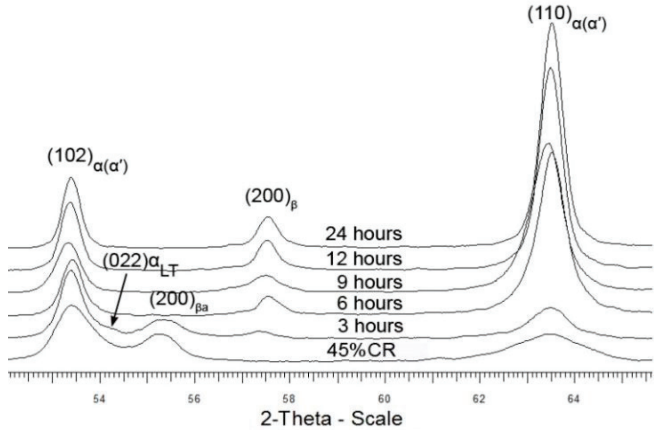


FIGURE 2. Diffraction patterns of the cold-rolled (45 %) rods after aging at 500 °C with various soakings

Meanwhile, we suppose that non-coherent phase boundaries of α-secondary precipitations are formed. As a result, the internal elastic stresses decrease significantly. The decrease of the full width at half-maximum (FWHM) of the α-phase peak in the diffraction pattern is an indirect evidence of a reduction in the internal stresses with the aging time increasing from 3 to 24 hours (Fig. 4).

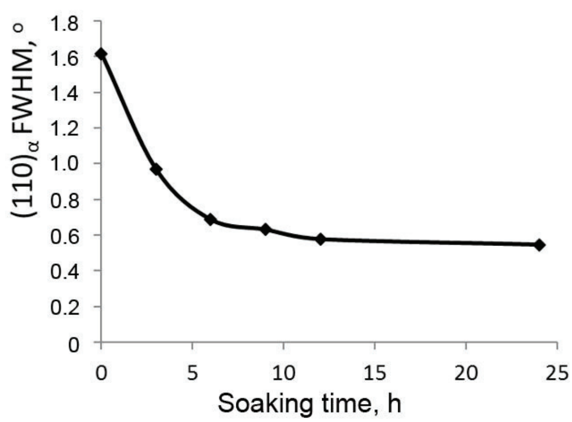
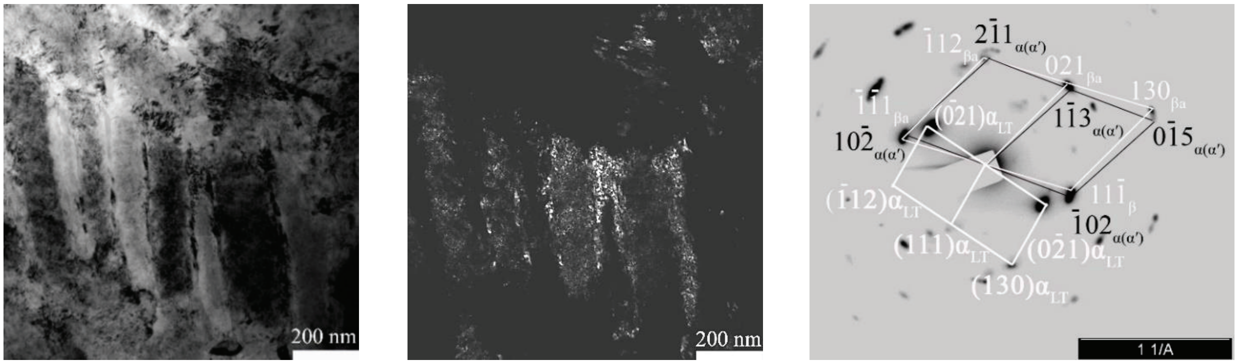


FIGURE 3. The effect of aging temperature on the FWHM of the (110)α diffraction peak

The analysis of the microstructure of the alloy aged for 3 hours and cold-rolled have revealed that the decomposition of the strain-induced α'-martensite is accompanied by the segregation of highly dispersed (less than 10 nm) particles of the low-temperature α_{LT}-phase. At the same time, the β_a-solid solution remains in the structure (Fig. 4c). Disperse secondary precipitations of α_{LT}-phase are mainly formed at the interface boundary. The strong strain contrast between the α_{LT}-phase precipitations and the α′-martensite is observed (Fig. 4a). It indicates the maintaining of the coherency of the boundaries between the α_{LT}- and α'-phases, which results in large elastic distortions [7]. This seems to be the reason for the formation of a high-strength state with low ductility. The fact is confirmed by the XRD examination of the specimens aged for 3 to 4 hours (Fig. 2).

The mechanical properties of the cold-worked VT16 alloy after aging at 500 °C for 3, 4, 16 and 24 hours are presented in Fig. 5. The data analysis has revealed that the increase in the soaking time of aging from 3 to 24 hours contributes to a significant change in the level of strength and ductility characteristics. The TS alters through a maximum corresponding to soaking for 4 hours. The elongation tends to increase from almost zero to 10 % along with increasing soaking time.



(a) (b) (c)

FIGURE 4. TEM data on the cold-worked VT16 alloy after aging at 500 °C for 3 hours: a – a bright-field image; b – a $(021)\alpha_{LT}$ dark-field image; c – a microdiffraction image and its interpretation, zone axes $[2\bar{5}\bar{1}]\alpha$, $[\bar{1}3\bar{2}]\alpha_{LT}$, $[\bar{3}1\bar{2}]\beta a$

The virtual absence of plastic deformation after the tensile tests of the specimens aged for 3 hours indicate brittle fracture. The fracture occurs at the elastic segment of the stress-strain diagram. The values of strength are lower comparing to the alloy aged for 4 hours, for which the elongation is about 4 %.

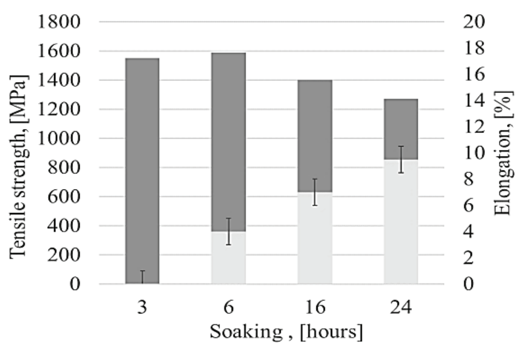


FIGURE 5. The effect of soaking during aging on the mechanical properties of the cold-worked VT16 alloy

A comparison of the strength characteristics of the alloy after LTTMT with the strength properties obtained during hardening heat treatment without cold rolling [8] show a definite advantage of thermomechanical treatment.

To sum it up, the low temperature thermomechanical treatment of the β-metastable VT16 alloy solution treated at β_{tr}-10 °C to α″-martensite has allowed us to obtain a high strength condition with UTS=1590 MPa and almost zero ductility after cold rolling to 45 % and aging at 500 °C for 3 hours. It has been established that this brittle state occurs due to the precipitation of the secondary low-temperature coherent α_{LT}-phase during decomposition of the products of strain-induced $\alpha''\rightarrow\alpha'+\beta_a$ transformation, which takes place upon cold-working. Increasing soaking time results in the formation of the equilibrium (α+β)-state characterized by TS > 1400 MPa and sufficient ductility (elongation above 7 %) after soaking for 16 hours.

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